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GIS-based environmental assessment of wind energy systems for spatial planning: A case study from Western Turkey

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ABSTRACT

Increasing population and life standards causes fossil fuel consumption to increase. Due to this increasing consumption, fossil fuels are being depleted rapidly. In addition to rapid exhaustion, another important problem associated with fossil fuels is that their consumption has major negative impacts on the environment. Therefore, many countries around the world have included renewable energy systems (RES) in their future energy plans so that they can produce reliable and environmentally friendly energy. Parallel to this trend, various RES have been identified and recently integrated into the current energy network of Turkey as well. However, it should be recognized that renewable energy resources are not fully environmentally safe. Different RES are associated with different environmental impacts. In planning the future energy development of a country, evaluation of renewable energy resources potentials together with their associated environmental impacts is critical. The aim of this study is to create a decision support system for site selection of wind turbines using Geographic Information System (GIS) tools. Wind energy potential and environmental fitness/acceptability are used as decision criteria for the site selection process. Potential environmental impacts of wind generation are identified in accordance with Turkish legislations and previous studies; and represented as fuzzy objectives of the decision problem. Wind potential map of Turkey generated by General Directorate of Electrical Power Resources Survey and Development is used to identify economically feasible locations in terms of wind energy generation. A study area composed of Usak, Aydin, Denizli, Mugla, and Burdur provinces in Turkey is selected and divided into 250 m $\times$ 250 m grids. Each grid represents an alternative location for a wind turbine or group of wind turbines. Fuzzy environmental objectives such as "Acceptable in terms of noise level", "Acceptable in terms of bird habitat", "Acceptable in terms of safety and aesthetics" and "Safe in terms of natural reserves" associated with wind turbines are identified based on previous research and each of these objectives are represented by a fuzzy set. Individual satisfaction degree of each of these environmental objectives for each grid is calculated. Then these individual satisfactions are aggregated into an overall satisfaction degree using various aggregator operators such as "and", "or", and "order weighted averaging." Thus, an overall satisfaction degree of all the environmental objectives is obtained for each grid in the study area. A map of environmental fitness is developed in GIS environment by using these overall satisfaction degrees. Then this map is utilized together with the wind potential map of Turkey to identify both potentially and environmentally feasible wind turbine locations within the study area.

Contents

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1. Introduction

While consumption of fossil fuels are increasing regardless of their adverse impacts on the environment, today, world's agenda focuses on sustainable energy systems to maintain continuous economic development and environmental sustainability. According to [1], the definition of sustainable energy is the combination of providing energy equally to all people and protecting the environment for next generations. In the light of this definition, new energy systems which respond to the needs of current and future populations should be adapted. The renewable energy systems (RES) have a common approval as a form of sustainable energy that keeps the attention recently [2].

Winds occur as a result of unequal distribution of solar heating around the world. The speed and the direction of wind can be various according to the characteristics of topography [3]. In [4], it is stated that similar to other renewable energy resources, people have taken advantage of wind power for many centuries until modern industrialization that caused people to deploy more reliable energy sources such as fossil fuels. However, the oil crisis which occurred in the mid-1970s made countries to invest more in new energy sources to eliminate the dependency on fossil fuels [5].

Utilization of renewable energy resources such as wind reduces the dependency on other countries for energy generation. Wind energy compared to fossil fuels causes less environmental damage. One of the major contributions of wind energy to environmental protection is through decreasing CO_2 emissions [6]. Wind turbines do not release any atmospheric emissions while generating power; nonetheless, there are still some negative impacts on both society and ecology [7]. The environmental impacts of wind energy which are commonly accepted by scientists are generally listed as effects on animal habitats such as bird collisions, noise generation, visual impact, safety issues, and electromagnetic interference.

Average bird collision to each wind turbine is in the range of 0.1–0.6 per year [8]. The rotating blades of wind turbines cause blur image on bird's eyes, therefore, birds construe that image as safe to go through, which leads to bird collisions [9]. In order to eliminate bird collisions, wind turbines should be located at a certain distance from bird flyways. According to [10], wind turbines must be located at least 500 m away from wildlife conservation areas. Another suggestion is that locating wind turbines at a minimum distance of 300 m away from bird habitat can provide bird protection [11].

A further impact of wind energy on habitat is noise. Although there are some regulations in terms of acceptable noise levels which depend on perception of communities, it is not easy to establish common noise principles [12]. Different authorities have different noise criteria, one of which claims that wind turbines should be located at least 500 m away from nearest habitat [1].

Visual impact, another side effect of the wind turbines, varies between individuals. According to [13], since the wind energy is constructing the clean energy image, some people might enjoy seeing them; on the other hand, the other people might consider it has adverse impacts on urban landscape. It is stated in [14] that wind turbines should be located 2000 m away from large settlements because of aesthetic concerns.

Even though a number of serious accidents have occurred, the safety record of wind energy is generally good that most of the accidents are due to poor management or noncompliance with safety regulations [12]. In [15] it is suggested that minimum distance from towns must be 1000 m for safety reasons and this same criteria is valid for reducing the visual impact as well. Wind energy in Vietnam is studied in [16] and it is concluded that a 2000 m buffer zone around city centers is unsuitable for wind energy development due to safety and visibility considerations.

According to [16], one other restriction that needs to be taken into account while selecting the location of wind turbines is their proximity to airport areas due to safety and visibility reasons. In [16] it is suggested that wind turbines should be at least 2500 m away from the nearest airport area. In addition, General Directorate of Civil Navigation in Turkey sets some restrictions about structures around airports. Basically, these restrictions aim to protect flight security, human lives, and property. In the first 3000 m zone there should not be any structure such as hospitals, schools or common buildings that may cause reflection. Buildings that are less than 45 m height are allowed with in the second 3000 m zone [17].

Moreover, wind turbines cause electromagnetic interference by scattering the electromagnetic waves from navigation and telecommunication systems [7]. Although television and radio signals may be affected by wind turbines which are located in a 2–3 km zone around the largest installation, today, cable networks or line-of-sight microwave satellite transmissions are eliminating the electromagnetic interference effect of wind energy [18].

Although the environmental impacts of wind energy are considerably tolerable with respect to those of conventional energy systems [19], they can further be reduced through utilization of appropriate site selection procedures for wind turbines locations. Therefore, before installing wind energy systems, comprehensive analyses should be conducted in order to identify the most favorable locations. GIS can have significant contribution as a decision support tool in identifying environmentally feasible locations for wind turbines which require management and analysis of wide range of spatial data types. GIS also offers tools both for technical tasks and analytical framework development. Sophistication level of GIS could change according to the purpose. It might just be used in order to provide maps for researchers, or it might provide data to apply distinct analyses and modeling [20].

Wind energy potential and various environmental concerns need to be evaluated together in identifying most suitable locations for wind turbines. Spatial multi-criteria decision analysis (MCDA) integrated with GIS allows incorporation of the geographical data with the decision makers' preferences in order to provide overall assessment of multiple, conflicting, and incommensurate criteria [21]. Thus, GIS analysis might aid to determine appropriate zones according to specific criteria for future development [22]. In this study, a GIS-based multi-criteria decision making methodology is proposed for selecting the most feasible location for installing wind turbines. Through multi-criteria decision making an overall environmental performance index is obtained for each alternative location and combined with the wind energy potential. The proposed methodology is then implemented on a study area in Turkey.

2. Methodology

The proposed methodology, which is given in Fig. 1, for site selection of wind turbines is explained in detail in this section. As can

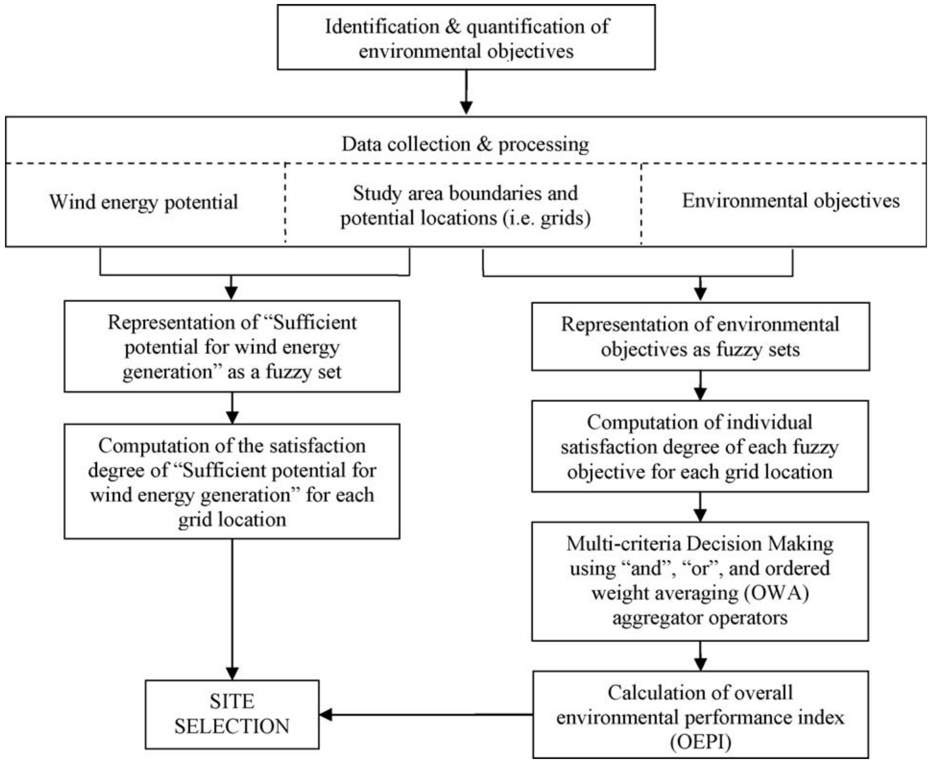

Fig. 1. Methodology of the study.

be seen from Fig. 1, the first step is identification and quantification of the environmental objectives. Then data related with environmental objectives, boundaries, and potential locations as well as the wind potential are collected and processed in GIS in order to obtain spatial data layers to be used in the site selection process. In the next step, identified environmental objectives are represented as fuzzy sets. The membership functions of these fuzzy sets are used to compute individual satisfaction degree of each potential location for each environmental objective in the GIS environment. The individual satisfaction degrees of each environmental objective are aggregated by using spatial multi-criteria decision making and an overall environmental performance index (OEPI) is calculated for each potential location. Parallel to this, wind energy potential is also represented as a fuzzy set and the membership function of this fuzzy set is used to generate a wind energy potential map in the GIS environment. Then OEPI layer is overlaid with wind potential maps and suitable locations for wind turbines are identified.

2.1. Identification and quantification of environmental objectives

Environmental objectives associated with energy generation with wind turbines are identified through a literature review and examination of government laws and regulations. These objectives are quantified with certain criteria. A criterion is a measurable aspect of a judgment, which makes it possible to characterize and quantify alternatives in a decision making process [23,24]. Environmental objectives and associated criteria identified through the literature review are given in Table 1. In addition, Turkish legislations associated with noise, safety, and natural reserves are used in indentifying environmental objectives associated with wind energy generation. These objectives and associated criteria are given in Table 2. Turkish legislation allows construction of wind energy turbines on forest areas, therefore, forest areas are considered environmentally acceptable in this study. According to national parks legislation, the structures which

Table 1
Environmental objectives and associated criteria from previous studies.

Environmental objectives	Criteria	Referance
Acceptable in terms of natural reserves	1000 m away from areas of ecological value	[14]
	400 m away from water bodies	[14]
	250 m away from ecologically sensitive areas	[10]
Acceptable in terms of safety and aesthetics for large city centers	2000 m away from large settlements	[14]
	2000 m away from cities, urban centers	[16]
Acceptable in terms of safety and aesthetics for town centers	Minimum 1000 m away from towns	[15]
Acceptable in terms of safety and aesthetics for airports	2500 m away from airports	[16]
	2500 m away from airports	[15]
Acceptable in terms of noise	500 m away from nearest habitat	[1,13,10]
	400 m away from nearest habitat	[18]
Acceptable in terms of bird habitat	At least 500 m away from wildlife conservation areas	[10]
	300 m from nature reserves to reduce risk to birds	[11]

Table 2
Environmental objectives and associated criteria from regulations.

Environmental objectives	Criteria	Regulation
Acceptable in terms of noise	Restriction for industrial areas: between 65 dBa and 55 dBa	Legislation of environmental noise evaluation/management (25/06/2002)
Acceptable in terms of bird habitat	At least 2.5 km buffer zone to protect ecologic and topographic features	Legislation of wetland protection (17/05/1994)
Safe in terms of natural reserves	Structures which have adverse impacts on habitat cannot be built	Legislation of national parks (12/12/1986)
Acceptable in terms of safety	Minimum distance is 3000 m and maximum distance is 6000 m	Notice of construction criteria around the airports (2007)

have adverse impacts on habitat cannot be built on national parks since these areas have to be preserved. Only the structures for visitors, management, and research are allowed [25].

2.2. Data collection and processing

For site selection, different map layers need to be collected. These layers include study area boundaries, potential locations for wind turbines, wind energy potential, settlement areas, roads, water bodies, natural reserves, etc. The study area is divided into regular grids with certain size and each of these grids is considered as a potential location for installation of wind turbines. In addition, criteria associated with each environmental objective (Tables 1 and 2) need to be represented by criterion maps. For example, a map layer of proximity to airports for ''Acceptable in terms of safety and aesthetics for airports'' objective is prepared by calculating each grid's distance to the nearest airport in the study area. Similarly various map layers are prepared for each environmental objective using the associated criteria given in Tables 1 and 2.

2.3. Representation of environmental objectives as fuzzy sets

Fuzzy membership functions for six environmental objectives, as identified in Table 1, are generated using the associated criteria given in Tables 1 and 2. As can be seen from Table 1, minimum distances of 250 m, 400 m, and 1000 m are suggested for ecologically sensitive areas, water bodies, and areas of ecologic value, respectively [10,14]. All of these criteria are integrated into a single restriction and represented with a fuzzy set named ''Acceptable in terms of natural reserves.'' The membership function for this fuzzy environmental objective is given in Fig. 2.

Another environmental objective is to maintain a power generation scheme which is ''Acceptable in terms of safety and aesthetics.'' As can be seen from Tables 1 and 2, different criteria are set for large settlements/urban centers, towns, and airports. In addition to these criteria, minimum and maximum buffer zones around airports are set by the notice of General Directorate of Civil Navigation. Minimum and maximum distances are set as 3000 m and 6000 m, respectively. Structures which may shine are not allowed in the first 3000 m zone, while buildings which are less than 45 m height are allowed in the second 3000 m zone [17].

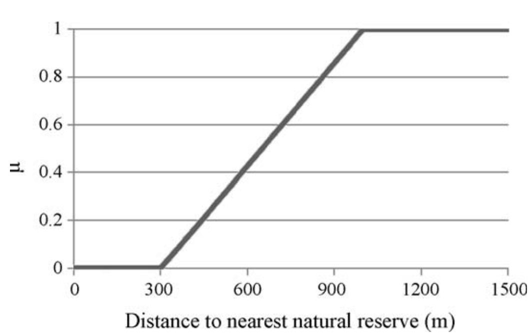

Fig. 2. Fuzzy set for ''Acceptable in terms of natural reserves''.

Three different fuzzy sets, ''Acceptable in terms of safety and aesthetics for large city centers'', ''Acceptable in terms of safety and aesthetics for town centers'', and ''Acceptable in terms of safety and aesthetics for airports'' are formed using the criteria provided in Tables 1 and 2 and are given in Figs. 3–5, respectively.

Noise is another environmental consideration that needs to be evaluated. As can be seen from Table 2, even though there are dBa restrictions for industrial areas (between 65 dBa and 55 dBa) in current noise legislation of Turkey, minimum required distances to settlements are not set [26]. The noise level of a wind turbine which has 1 MW power is expected to be 45 dBa at a distance of 300 m [27]. In addition, as can be seen from Table 1, 400 m and 500 m are identified as tolerable levels in four different studies. All of these criteria are used to define the membership function of the fuzzy set ''Acceptable in terms of noise'' and it is given in Fig. 6.

Bird migration pathways and a certain buffer zone along these pathways are not appropriate locations for wind turbines. Furthermore wetlands and protection zones are main locations of bird habitat. Wetlands and protection zones are determined by Ministry of Environment and Forestry in Turkey. According to the Turkish legislation about wetlands [26] there must be at least 2.5 km buffer zone to protect ecologic and topographic features of these areas (Table 2). The fuzzy membership function for ''Acceptable in terms of bird habitat'' is formed by using the information provided in Tables 1 and 2, and is given in Fig. 7.

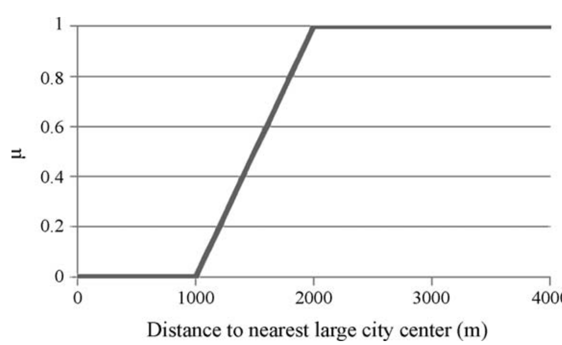

Fig. 3. Fuzzy set for ''Acceptable in terms of safety and aesthetics for large city centers''.

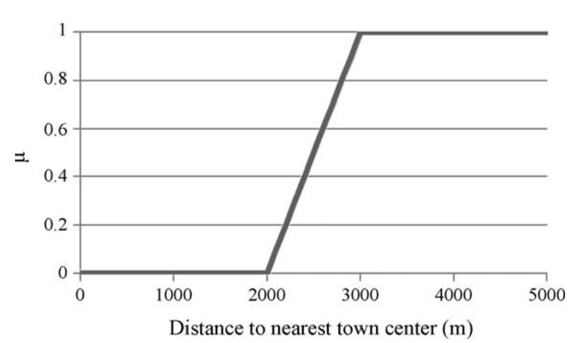

Fig. 4. Fuzzy set for ''Acceptable in terms of safety and aesthetics for town centers''.

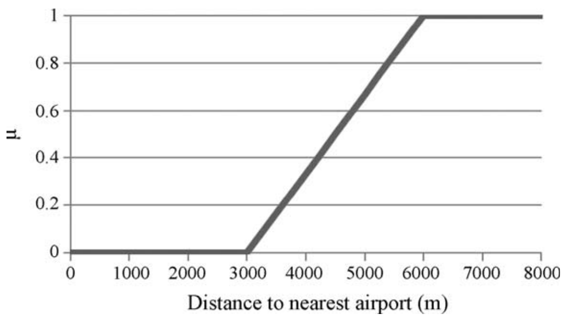

Fig. 5. Fuzzy set for "Acceptable in terms of safety and aesthetics for airports".

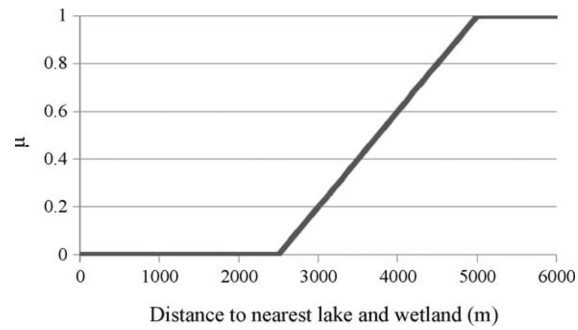

Fig. 7. Fuzzy set for "Acceptable in terms of bird habitat".

2.4. Computation of individual satisfaction degrees

The generated membership functions are used to compute individual satisfaction degree of each potential location (i.e. grid point) for each environmental objective. To calculate and store all the required information for individual satisfaction degrees of each fuzzy environmental objective, a separate layer is created in the GIS environment. For example, in the layer corresponding to "Acceptable in terms of noise", data related with housing areas is stored since the noise level of the wind turbines should not disturb the population in the residential area. The individual satisfaction degree of each fuzzy environmental objective for each grid is evaluated by using the data stored in these layers.

Membership function of the fuzzy environmental objective is used to determine the fulfillment degree of this objective by each potential location. These individual satisfaction degrees are recorded in a separate column in the GIS database. The next step is to aggregate these individual satisfaction degrees into an OEPI.

2.5. Multi-criteria decision making (MCDM)

Multi-criteria decision making is used to evaluate a set of alternatives which are derived from contradictory and incommensurate criteria. MCDM can be grouped in two sub-classes: multi-attribute decision making (MADM) and multi-objective decision making (MODM). MADM and MODM involve single-decision making problems and group decision problems that can be further categories into deterministic, probabilistic, and fuzzy decisions [21]. In this study, "and", "or", and "ordered weighted averaging (OWA)" aggregation operators are used as MODM tools in evaluating alternatives with respect to various fuzzy environmental objectives.

Most commonly used aggregation operators are "and" and "or" operators and they are used to represent two extreme cases: "Satisfaction of all the desired criteria" and "Satisfaction of any of the desired criteria", respectively [28]. However, in some cases, decision makers may want to perform an aggregation which lies in between these two extreme cases. For such situations, Yager [28] proposed the OWA function which combines "and" and "or" operators which is called an "orand" operator. The rationale of this application is to aggregate the attributes not by classical weighted average but by ordered position of the attributes.

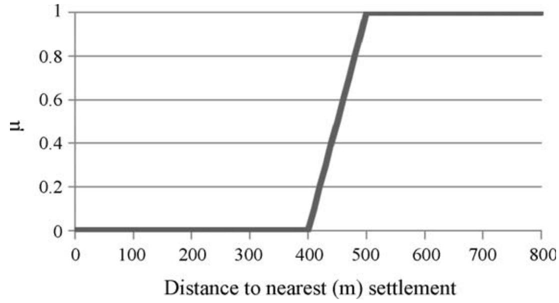

Fig. 6. Fuzzy set for "Acceptable in terms of noise".

"And" operator: t-norms are a way to apply "*anding*" operators for decision makers who desire to satisfy all of the criteria. t-Norms operators enable implementation of fuzzy set aggregation. It is noted by [29] that t-norm is a way to find Pareto optimal solution because of its monotonic properties. In other words, if one of the alternatives has a zero satisfaction degree, evaluation of overall satisfaction degree returns zero. For instance, if the decision makers want to satisfy all of the n criteria, $\overline{F_i}$, $i = 1, \ldots, n$, then this can be represented by:

$$D = \overline{F_1} \cap \overline{F_2} \cap \ldots \cap \overline{F_n} \tag{1}$$

The bar sign on capital letters is used to represent fuzzy sets.

The following theorem expresses the important property of t-norm operator: considering T corresponds to the t-norm operator, then for any a and b: $T\ (a,\ b) \leq Min\ (a,\ b)$. The result of implementation of "*anding*" operators allows for no compensation for one bad satisfaction in multi-criteria decision making [28].

"OR" operator: t-Conorms are aggregation operators which correspond to the "*oring*" operators. If decision makers want to satisfy any of the criteria, t-conorms can achieve this goal. For this purpose, union operator is used in order to connect the criteria as follows [29]:

$$D = \overline{F_1} \cup \overline{F_2} \cup \ldots \cup \overline{F_n} \tag{2}$$

The following theorem expresses the important property of t-conorm operator: considering S corresponds to the t-conorm operator; then for any a and b: $S\ (a,\ b) \geq Max\ (a,\ b)$. The result of implementation of "*oring*" operators allows for no distraction from one good satisfaction in multi-criteria decision making [28].

Ordered weighted averaging (OWA): OWA aggregation concept was first suggested by Yager [28]. A mapping f from $I^n \rightarrow I$ (where $I = [0,1]$) is called an OWA operator of dimension n if associated with f is a weighting vector W, $[W_1, W_2, \ldots, W_n]^T$ such that

(1) $W_i \in (0,1)$
(2) $\sum_i W_i = 1$
where

$$f(\mu_{S,1}, \mu_{S,2}, \ldots, \mu_{S,n}) = W_1 b_1 + W_2 b_2 + \ldots + W_n b_n \tag{3}$$

where b_i is the ith largest element of $\mu_{S,1}, \mu_{S,2}, \ldots, \mu_{S,n}$ [28,29]. The aggregation operation is represented by f, and the individual satisfaction degree of each alternative, S for fuzzy objective $\overline{F_i}$ is represented by $\mu_{S,i}$. The distinction of OWA operator from other aggregation methods is based on the fact that the weights are assigned to the criteria not according to a particular element, but a particular ordered position [28].

Quantifier guided OWA combination: decision makers' attitudes toward the solution may not always be like "all of the criteria

must be satisfied'' or ''any of the criteria must be satisfied'' but they may desire just some proportion of the criteria to be satisfied. For example, satisfaction of ''most'', ''few'', ''at least 20 percent'', and ''many criteria'' can be required for an acceptable solution [29]. Linguistic quantifiers such as ''most'', ''many'', ''at least half'', ''some'', and ''few'' can be implemented by mathematical tools of fuzzy set theory and this allows inclusion of decision makers' attitudes into the decision process. Mathematical expressions of the natural language can be obtained by fuzzy logic; hence, it allows us to construct multi-criteria decision functions [29].

The structure of OWA operator is suitable for combining the objectives under the guidance of a quantifier. The process of determining the best location using linguistic quantifier $\overline{Q}$ is called quantifier guided aggregation. The linguistic quantities can be represented as a fuzzy set $\overline{Q}$ of the unit interval. In this representation, for each $y \in I$, $Q(y)$ indicates the degree to which the proposition y satisfies the concept denoted by $\overline{Q}$ [29,30]. The decision maker feels satisfaction of $\overline{Q}$ fuzzy objectives is necessary for a good solution.

Relative quantifiers can be expanded into three sub-categories [30]: (1) Regular Increasing Monotone (RIM) quantifier such as ''all'', ''most'', ''many'', and ''at least α'', (2) Regular Decreasing Monotone (RDM) quantifier such as ''at most one'', ''few'', ''at most α'', and (3) Regular UniModal (RUM) such as ''about α''.

In order to obtain the overall satisfaction degree of an alternative, individual satisfaction degree with respect to each criterion need to be aggregated in a way to represent decision makers' attitude. In this study, we believe that satisfying ''*most*'' of the environmental objectives (i.e. $\overline{Q}$ represents ''*most*'' of the criteria) is a reasonable expectation. Thus $\overline{Q}$ is a RIM quantifier. For this purpose weights are generated as follows:

$$w_i = Q\left(\frac{i}{n}\right) - Q\left(\frac{i-1}{n}\right), \quad \text{for} \quad i = 1, 2, \ldots, n \tag{4}$$

In this study, we assume that the guided quantifier ''*most*'' is defined as $Q(r) = r^2$ [29,30].

Decision maker's attitude is important in selecting the aggregation operator. For example, if decision maker considers the worst case scenario which represents the ''pessimistic attitude'', a minimum operator is a proper choice. On the contrary, maximum operator is the choice to represent an optimistic attitude. However, as explained earlier, in some situations, the decision maker may prefer to satisfy ''most of the criteria'', ''at least half of the criteria'', ''more than 20 percent of the criteria'', etc. OWA operator is helpful in terms of obtaining decision maker's attitude by converting these linguistic specifications to mathematical values which do not have to be the extreme cases [31].

In order to investigate the impact of the decision maker's attitude in the final decision, different aggregation operators are tested in this study: (i) the OWA for ''Satisfaction of most of the environmental objectives'', (ii) ''and'' operator for ''Satisfaction of all the environmental objectives'', and (iii) ''or'' operator for ''Satisfaction of any of the environmental objectives.'' To evaluate ''Satisfaction of most of the environmental objectives'' quantifier guided aggregation is used. At the end of MCDM step, three different OEPI values are calculated for each potential location. Since OEPI values obtained by OWA operator represent a more realistic condition (i.e. ''Satisfaction of most of the environmental objectives''), the results of OWA aggregator are used in determining the most suitable location for wind turbines.

2.6. Representation of wind energy potential as a fuzzy set

Wind energy potentials associated with the grid points are not included in the OEPI calculations. However, while performing site selection, both the wind energy potential and environmental acceptability/fitness need to be considered. A location which does not have sufficient wind energy potential is not an appropriate location for wind turbines no matter how high its OEPI is. Thus, the next step is to obtain the available wind energy potential map of the study area.

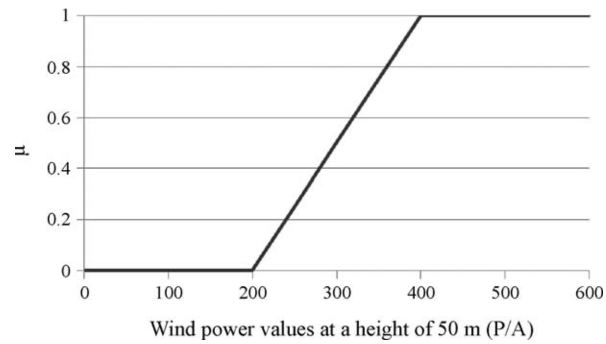

Fig. 8. Fuzzy set for ''Sufficient potential for wind energy generation''.

During interviews with the General Directorate of Electrical Power Resources Survey and Development Administration, it became clear that economically feasible power values for generating wind energy in Turkey are between 300 $\dot{P}/A$ and 400 $\dot{P}/A$ (power/area as W/m^2). However, in Europe satisfactory values start from 200 $\dot{P}/A$ [32,33]. In order to quantitatively represent sufficient/feasible wind energy potential, a fuzzy set named ''Sufficient potential for wind energy generation'' is formed using this information. The membership function of this fuzzy set is given in Fig. 8. The wind energy potential map of the study area is used to generate wind potential layer in the GIS environment. ''Sufficient potential for wind energy generation'' fuzzy set and the wind energy potential layer is used together to calculate a degree of satisfaction for ''Sufficient potential for wind energy generation.''

2.7. Site selection

At the end of the procedure given in Fig. 1, each grid is associated with a degree of satisfaction for ''Sufficient potential for wind energy generation'' and ''Satisfaction of most of the environmental objectives'' (i.e. OEPI). Each grid point needs to be evaluated based on these two criteria. Aggregation of satisfaction degrees of these two criteria is another decision making process. The proposed decision criteria for site selection of wind energy systems are given in Table 3. As can be seen from Table 3, only the grid points which satisfy both ''Sufficient potential for wind energy generation'' and ''Satisfaction of most of the environmental objectives'' with a degree of at least 0.5 are identified as appropriate wind turbine locations. These grids can be referred to as ''priority sites'' for wind energy generation. Priority sites can be identified in the GIS environment using the ''and'' operator with the following procedure: degrees of satisfactions for ''Sufficient potential for wind energy generation'' and ''Satisfaction of most of the environmental objectives'' are aggregated by the ''and'' operator to give an overall performance index and grids with an overall performance index of 0.5 and higher are selected.

3. Example application

The proposed methodology for site selection of wind turbines is applied for a study area in the western part of Turkey. The study area is composed of Aydin, Usak, Burdur, Denizli, and Mugla provinces. A detailed map of the study area and location of the study area within Turkey is given in Fig. 9. High wind power

Table 3
Site selection criteria for wind energy systems.

Degree of satisfaction for "Sufficient potential for wind energy generation"	Degree of satisfaction for "Satisfaction of most of the environmental objectives"	Decision for the grid (i.e. alternative)
0.0–0.5	0.0–0.5	Eliminate—due to both insufficient potential and environmental concerns
0.0–0.5	0.5–1.0	Eliminate—due to insufficient potential
0.5–1.0	0.0–0.5	Eliminate for now—due to environmental concerns. Consider remedial actions and reevaluate
0.5–1.0	0.5–1.0	Mark as priority site for wind energy generation

Fig. 9. Study area.

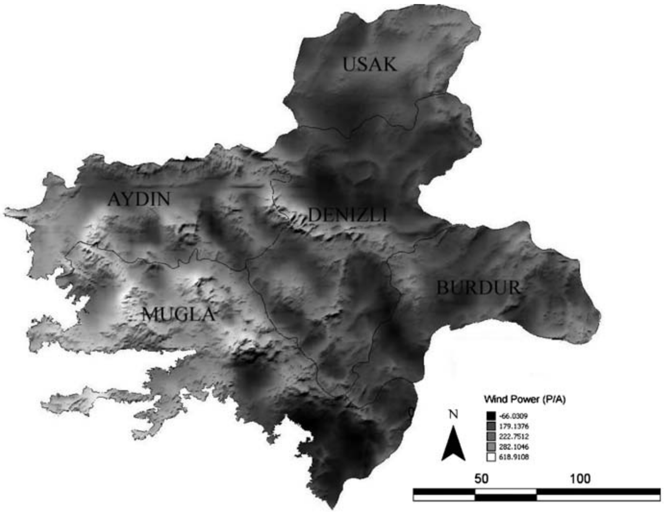

Fig. 10. Current wind potential map of the study area.

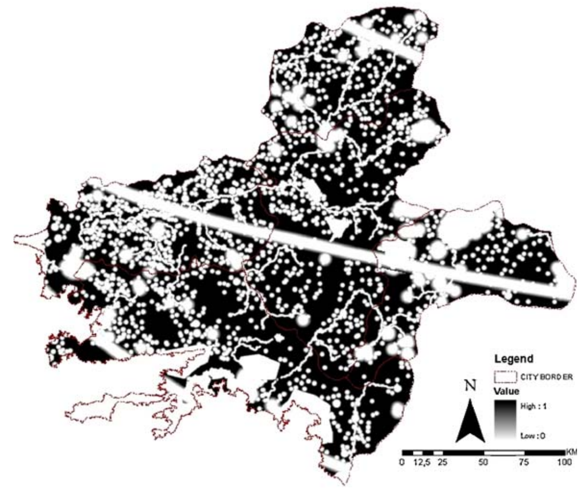

Fig. 12. OEPI map for "Satisfaction of all of the environmental objectives".

potential of the study area makes it attractive for renewable energy investors. The current wind potential map of the study area is obtained from General Directorate of Electrical Power Resources Survey and Development Administration and is given in Fig. 10. Wind energy potential map contains available power values at a height of 50 m.

First, associated layers for wind energy potential, settlement areas, roads, water bodies, natural reserves, wetlands, bird migration pathways, and airports are obtained for the study area. As explained earlier, environmental criteria associated with wind energy generation are identified and represented as fuzzy sets (see Figs. 2–7). Then 250 m point grids are created for the whole study area in ArcGIS 9.2 software. Individual satisfaction degrees of each fuzzy environmental objective for each grid location are evaluated by using GIS tools and they are aggregated into an OEPI. The attitude of the decision maker is included in the decision making process through utilization of different aggregation operators. In this study, "Satisfaction of most of the environmental objectives" (i.e. OWA), "Satisfaction of all the environmental objectives" (i.e. "*anding*") and "Satisfaction of any of the environmental objectives" (i.e. "*oring*") are investigated. OEPI of wind energy associated with "Satisfaction of most of the environmental objectives" is given in Fig. 11.

In Fig. 11, black represents a membership value of 1 while white represents a membership value of 0 in the fuzzy set "Satisfaction of most of the environmental objectives." In other words, the black grids are the ones where the fuzzy objective of satisfying most of the environmental objectives is fully satisfied. As can be seen from Fig. 11, a big portion of the study area (i.e. black regions) satisfies most of the environmental objectives. The vertical gray band passing through the study area represents a bird migration route. As expected the compatibility of this band with "Satisfaction of most of the environmental objectives" fuzzy set is less than one (i.e. it is marked with gray instead of black on the map). Similarly, areas close to lakes and other water bodies, large city centers, natural reserves, town centers, airports are maked with different tones of gray which indicates various satisfaction degrees in between zero and one. The tone of gray is governed by the proximity of the grid point to these locations.

Aggregation operators "and" and "or" are used as well to generate OEPI for "Satisfaction of all of the environmental objectives" and "Satisfaction of any of the environmental objectives", respectively. The OEPI maps for "and" and "or" operators are given in Figs. 12 and 13, respectively. The "and" operator represents the worst case scenario. As can be seen from Fig. 12, the bird migration route is

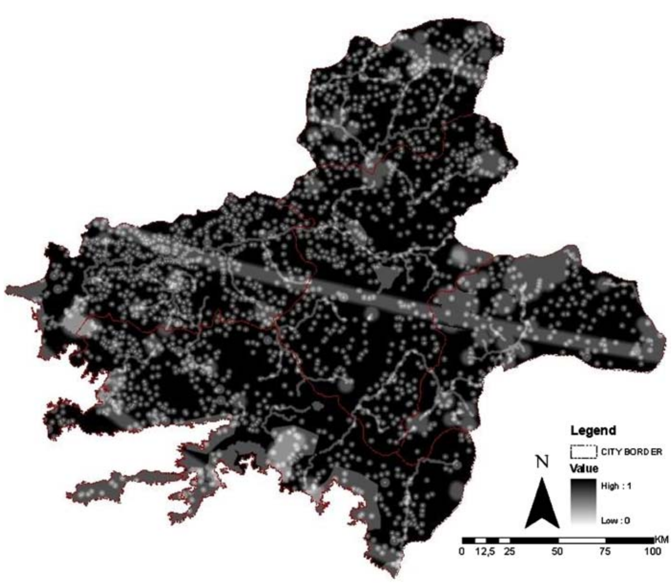

Fig. 11. OEPI map for "Satisfaction of most of the environmental objectives".

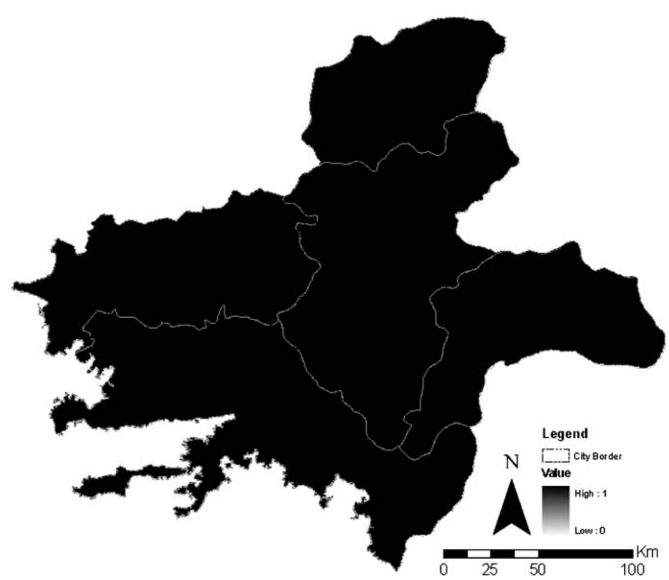

Fig. 13. OEPI map for "Satisfaction of any of the environmental objectives".

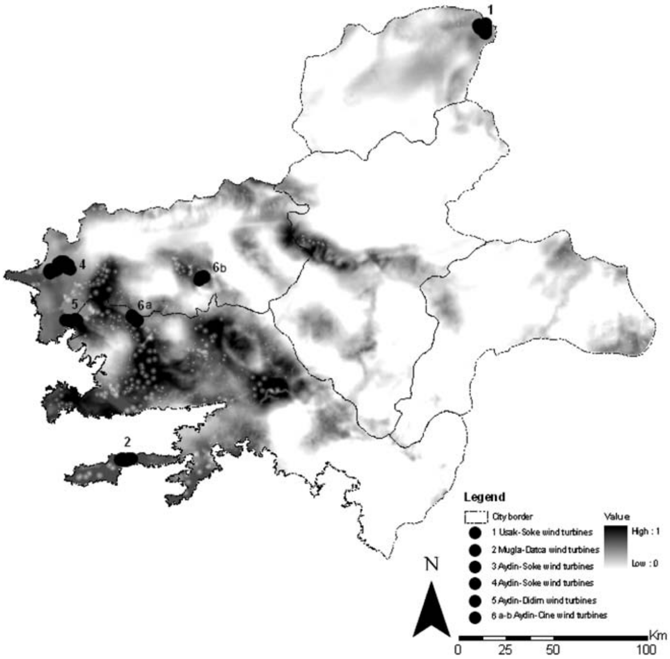

Fig. 14. OPI map.

marked with a white band (i.e. membership function value for "Satisfaction of all of the environmental objectives" fuzzy set is zero) this time. Since "Satisfaction of all of the environmental objectives" is required and the bird migration route has an individual satisfaction degree of zero for "Acceptable in terms of bird habitat" fuzzy objective the overall satisfaction degrees for the grids located in this bird migration route band become zero. Similarly, all water bodies, large city centers, natural reserves, town centers, airports are marked with white zones in Fig. 12. Not having many gray zones in Fig. 12, indicates that most of the grid points either satisfy all the fuzzy objectives (i.e. overall satisfaction degree is one and consequently the grid is marked with black) or there is at least one fuzzy objective which is not satisfied at all (i.e. the grid has an individual satisfaction degree of zero for at least one of the fuzzy objectives). "Satisfaction of any of the environmental objectives" requirement produces a map which is completely black (see Fig. 13). This indicates that all the alternatives (i.e. potential locations) fully satisfy at least one of the fuzzy objectives. Thus, OEPI for all grids are one.

Wind energy potential map of the study area (Fig. 10) is used together with the membership function of "Sufficient potential for wind energy generation" fuzzy set and a satisfaction degree is calculated for each grid point. The satisfaction degree is an indication of how much each grid location belongs to "Sufficient potential for wind energy generation" fuzzy set. In other words, the fuzzy set converts wind energy potential of each grid into a value in the range [0,1]; 0 representing not sufficient potential for wind energy generation and 1 representing completely sufficient potential for wind energy generation. Now, degrees of satisfaction for "Sufficient potential for wind energy generation" and "Satisfaction of most of the environmental objectives" (i.e. OEPI) are calculated for each grid point. These two satisfaction degrees together with decision criteria given in Table 3 are used to evaluate suitability of each grid point for installation of wind turbines. As can be seen from Table 3, only the grids which satisfy both "Sufficient potential for wind energy generation" and "Satisfaction of most of the environmental objectives" with a degree of at least 0.5 are identified as appropriate wind turbine locations. Thus an overall performance index (OPI) is calculated for each grid point by aggregating the satisfaction degrees of "Sufficient potential for wind energy generation" and "Satisfaction of most of the environmental objectives" with "and" operator. Grid points with an OPI value of 0.5 can be referred to as priority sites for wind energy generation.

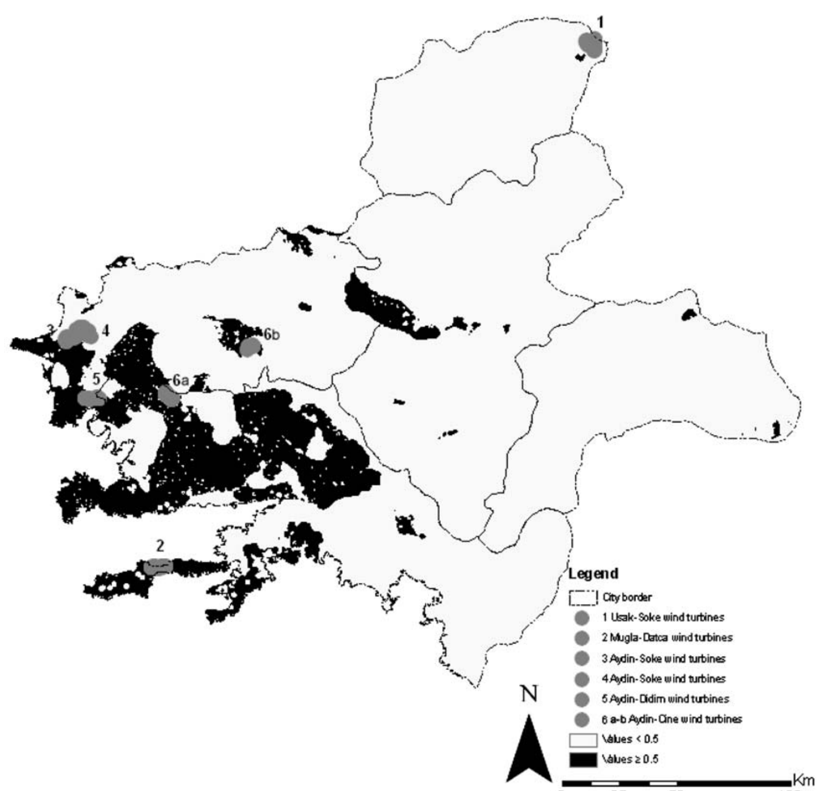

Fig. 15. Priority sites.

First OPI for each grid point is calculated for the study area and provided in Fig. 14. Then grid points with an OPI of 0.5 and higher are determined and given in Fig. 15. As can be seen from Fig. 15, light gray areas (i.e. grids with an OPI of 0.5 and smaller) of Fig. 14 are eliminated from the priority sites. However, it should be noted here that these grids may be turned into priority sites with implementation of appropriate environmental measures. Thus, these locations require further study and reevaluation. Already existing wind turbine locations are marked in Figs. 14 and 15. As can be seen from Fig. 15, some of the existing wind turbines are located in priority sites. It can be concluded that locations of these existing turbines are acceptable with respect to the procedure presented in this study.

4. Conclusions

It is well accepted that renewable energy resources have advantages over conventional energy systems in terms of environmental acceptability. However, as explained in this paper, RES are associated with various environmental impacts as well. Thus, combined evaluation of the wind potential and environmental impacts is required for the site selection process of wind turbines.

Renewable energy investments have been increasing in Turkey. According to 2009 data of General Directorate of Electrical Power Resources Survey and Development Administration, there are 17 operating wind turbines, 7 wind turbines are still under construction, and companies had procurement contract in order to obtain wind turbines for 15 different wind farm constructions in Turkey [33]. In addition, there were 117 applications for producing wind energy, 53 licenses were given to private companies [33]. As these numbers indicate contribution of wind energy to the energy budget of Turkey is going to increase in the future. Thus, identification of environmentally and potentially suitable locations for wind turbines is soon going to become an important issue for Turkey. Decision makers should consider both potential and economical feasibility together with environmental fitness of each prospective wind farm while assigning licenses. The tradeoffs between wind potential and environmental acceptability need to be evaluated carefully. The approach developed in this study will help decision makers to achieve this goal.

In this study, a decision support tool for site selection of wind energy turbines is developed in the GIS environment using fuzzy decision making approach. This decision support tool enables aggregation of individual satisfaction degrees of each alternative location (i.e. grid) for various fuzzy environmental objectives into an OEPI. Grids with higher OEPI are environmentally preferable/feasible locations to implement RES development. Of course environmental feasibility is not sufficient in identifying priority sites for wind energy generation. The wind energy potential of the location is the determining factor for site selection of wind turbines. Wind energy potential of each grid is represented by the satisfaction degree of that grid in ''Sufficient potential for wind energy generation'' fuzzy set.

Degrees of satisfactions for ''Sufficient potential for wind energy generation'' and ''Satisfaction of most of the environmental objectives'' are aggregated by the ''and'' operator to give an OPI. Grids with an OPI of 0.5 and higher are selected as priority sites which are appropriate sites for installation of wind turbines. Priority sites are environmentally preferable sites which have sufficient wind potential.

As a case study, the priority sites for a study area which is composed of Usak, Aydin, Denizli, Mugla, and Burdur provinces in Turkey is generated in the GIS environment and existing wind turbine locations are marked on this map as well. Some of the existing wind turbines are located inside the priority zones defined in this study. More important than evaluating if the existing wind turbine locations are appropriate; the priority map can be used in assigning permits for future wind turbine installations. Although the procedure suggested here is developed for wind energy, it is general and can be used in developing priority maps for other renewable energy resources such as solar, geothermal, biomass, etc. as well. This is the topic for future research.

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